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INTRODUCTION

Exhaust gas inhalation is responsible for approximately two-thirds of the deaths in building fires.[1,2] Many fatalities in building fires occur in enclosed locations remote from the burning compartment.[3] A major component of the fire exhaust gases which are transported throughout a building is the odorless and colorless gas, carbon monoxide.[4]

In 1987, three people died due to carbon monoxide poisoning in the upstairs of a townhouse in Sharon, Pennsylvania. Extremely high levels of carboxyhemoglobin, 91%, were present in one of the victim's bloodstream. This prompted an investigation by NIST/BFRL to simulate the townhouse fire.[5] The source of the fire was in the kitchen of the townhouse where a large amount of wood (wood paneling and cabinets) was located. The CO levels exiting the kitchen were found to be as high as 8.5%-dry, while the levels upstairs where the bedrooms were located was 5.0%-dry.[6] Experiments performed by Pitts[6] and his coworkers in a reduced-scale compartment with the ceiling and the upper-portion of the walls lined with wood showed the CO concentrations were 6%-dry or greater in the rear and 12%-dry in the front of the compartment. This was a dramatic increase from the CO concentrations, approximately 4%-dry in the front and 3%-dry in the rear, seen in the non-combustible compartment.[6]

The portion of the building fire research ongoing at VPI & SU presented herein involves an investigation of the evolution of exhaust gases from an underventilated liquid hexane pool fire inside a reduced-scale compartment with and without a Douglas fir plywood ceiling. The work focused on the production of carbon monoxide (CO) and unburned hydrocarbons (UHC) inside the compartment and the transport and oxidation of the fire exhaust gases in a corridor adjacent to the burning compartment. The results of the experiments were compared to those reported by Pitts[6].

EXPERIMENTAL

The investigation of compartment fire exhaust gas production, transport and oxidation was performed in the reduced-scale compartment fire facility at VPI&SU shown in Figure 1. A detailed description of the apparatus is given elsewhere.[7]

In the experiments with a combustible ceiling, 3 sheets of 0.91 m long, 0.30 m wide, 6.35 mm thick Douglas fir plywood were hung from the ceiling of the compartment. The mass of the wooden ceiling, initially 4.67 kg ± 0.21 kg, was continuously monitored during the tests with a load cell assembly.

In the present investigation, two different types of compartments were used. In the window-case experiments, the air was naturally drawn into the compartment from the air distribution plenum through the two thermally shielded vents at floor level, see Figure 1. The exhaust gases exited the compartment through the scaled window, 0.51 x 0.24 m (1200 cm^2), and were subsequently transported down the hallway. For the door-case, both the fresh air and the exhaust gases were transported in and out, respectively, of the compartment through the scaled door opening, 0.51 x 0.75 m (3825 cm^2), at the compartment-hallway interface. The air distribution plenum was blocked off from the ambient air, so air was allowed to enter the compartment only through the door.

Sampling of the exhaust gases was done at two locations in the upper layer of the compartment and at three locations along (the length) of the hallway. The in-compartment sampling was done 0.10 m from the wall containing the exhaust vent (the front of the compartment) and 0.10 m from the wall opposite the exhaust vent (the rear of the compartment). Both in-compartment sampling probes were located 0.10 m from the ceiling and 0.23 m from the side wall. The hallway sampling was done in the center of the corridor, 0.05 m below the ceiling. The sample gas concentrations of O_2, CO_2 and CO are reported on a dry basis while the UHC are reported on a wet basis. Vertical temperature profiles were measured at one location within the compartment and in the hallway at the sampling locations given above.

To determine the global equivalence ratio inside the compartment during the "quasi"-steady-state of the fire, the air entrainment into the compartment and the fuel vaporization rate must be known. The fuel vaporization rate was measured by constantly monitoring the fuel weight using a load cell. In the window-case, the air entrainment rate into the compartment was determined by measuring the mass flow of the air in the duct connected to the plenum. The air entrained into the compartment was estimated in the door-case using the ventilation factor first developed by Kawagoe (1958),

$$\dot{m}_{air} = kA_w H^{1/2} \quad \text{[kg/s]} \qquad (1)$$

where A_w is the area of the door in m^2, H is the height of the doorway in meters and k is a constant taken to be 0.25. The relationship shown in Equation (1) is only valid during the period when the compartment fire is underventilated.

The points on the graphs to follow were formed by averaging the experimental data points during a 20 second time window while external burning occurred inside the hallway.

RESULTS AND DISCUSSION

Species concentrations and temperatures within compartment and the hallway with a non-combustible ceiling in the compartment for the window-case are shown in Figure 2. In the experiments used to generate this figure, the average fire size was 535 kW and the average global equivalence ratio was 2.50. The origin of the abscissa corresponds to the exhaust vent at the compartment-hallway interface. Negative axial distances are inside the compartment, while positive axial distances are inside the hallway. The concentrations of CO and UHC at the rear of the compartment were 3.14% and 2.29%; respectively, while they were 4.08% and 6.53%; respectively, at the front of the compartment. These are comparable to the levels previously noted by other researchers.[6,9] The UHC were oxidized faster than CO down the length of the hallway for two reasons. The oxidation rate of UHC at temperatures up to approximately 1100K is higher than that of CO[10], partially explaining the more rapid reduction in the UHC concentration. In addition, CO was formed when the UHC were oxidized, thus generating additional CO within the hallway upper-layer. Near the end of the hallway, the oxidation reaction rates of CO and UHC began to fall rapidly ("freeze-out") when the gas temperature decreased below 950K.1[1] When this occurred, less of the entrained air was used in the oxidation of CO and UHC causing the remaining oxygen to dilute the upper-layer gases. This is seen in Figure 2 through the increase in the levels of O_2 and a decrease in the levels of all the measured product gases (CO_2, CO and UHC). By the exit of the hallway, the concentration levels of CO and UHC had decreased 86% and 96%; respectively, from their highest in-compartment levels.

When a combustible ceiling was added to the scaled-window compartment, the species concentrations and temperatures inside the facility changed drastically, see Figure 3. The total fire size was 1131 kW with 446 kW produced by the hexane fire and 685 kW produced by the wooden ceiling. These fires had an average equivalence ratio of 4.77. The higher equivalence ratios were expected since fuel (wood) was burning in the upper-layer of the compartment. The in-compartment levels of CO increased to 13.6% in the rear and 12.6% in the front which is comparable to the levels noted by Pitts[6]. The UHC concentrations within the compartment experienced a slight increase to 7.29% in the rear and 7.88% in the front. The gas temperature within the compartment dropped 100K with the presence of the wooden ceiling. This was also observed by Pitts[6], and was attributed to the pyrolysis of wood being an endothermic process. The burning of the fuel rich exhaust gases down the corridor produced inside the compartment caused the hallway upper-layer temperatures to increase until approximately 1.8 m down the corridor. The increase in the temperature did allow the gases to continue to be oxidized along the entire length of the hallway. By the exit of the hallway, though, the CO had been only been reduced by 79% of the highest in-compartment level, while the UHC had been reduced by 82% of its highest in-compartment level. This reduction is less efficient than what was seen in the non-combustible ceiling case.

Gas species concentrations and temperatures within the facility with a non-combustible ceiling in the compartment and a scaled door connecting the compartment and hallway are shown in Figure 4. The average fire size for these experiments was 546 kW while the average equivalence ratio was 2.23. The concentrations of CO inside the compartment were slightly higher than those seen in the window-case, while the UHC concentrations were slightly lower. When the gases exited the compartment through the upper-portion of the door, two large vortical structures formed at doorway rotating from the outside of the door towards the middle of the door. Again, the UHC oxidized faster than CO, but the oxidation of UHC and CO did not extend nearly as far down the hallway as was seen in the window-case. By the end of the hallway, the CO and UHC concentrations were reduced by 94% and 98%; respectively, from the maximum in-compartment value. The improved oxidation of the exhaust gases is attributed to the increased entrainment of hallway air into plume at the door caused by the presence of the larger vertical plume and vortical structures present here.

Shown in Figure 5 are the species concentrations and gas temperatures of the exhaust gases produced by a hexane fire in a scaled door compartment containing a wood ceiling. The total compartment fire size was 1397 kW; 495 kW from the hexane fire and 902 kW from the wooden ceiling. The equivalence ratio for these cases averaged 4.25. The concentrations of CO inside the compartment were found to be slightly lower than those in the window-case, but were still much higher than those levels seen in the door-case with no combustible ceiling. The UHC concentrations were slightly higher than the levels seen in the window-case. The temperature within the compartment was approximately 100^K lower than that seen in the non-combustible compartment with a doorway, similar to the corresponding window-case. Again, the temperature within the hallway continued to rise until the exhaust gases had traveled down the hallway approximately 1.8 m from the compartment. The concentration reduction of CO and UHC at the exit of the hallway, by 88% and 94%; respectively, from the maximum in-compartment level.

SUMMARY AND CONCLUSIONS

The presence of a wooden ceiling within the compartment was seen to have a dramatic effect on the CO levels produced during a compartment fire, while the levels of UHC were seen to increase slightly. The temperature in the compartment containing the combustible ceiling was found to be lower than for the compartment with a non-combustible ceiling. With the combustible ceiling in the compartment, the burning of the fuel rich gases caused the gas temperature in the hallway to peak 1.8 m down the hallway from the compartment. Compared to the non-combustible ceiling cases, the combustible ceiling cases experience less of a reduction in the compartment concentrations of CO and UHC by the end of the hallway.

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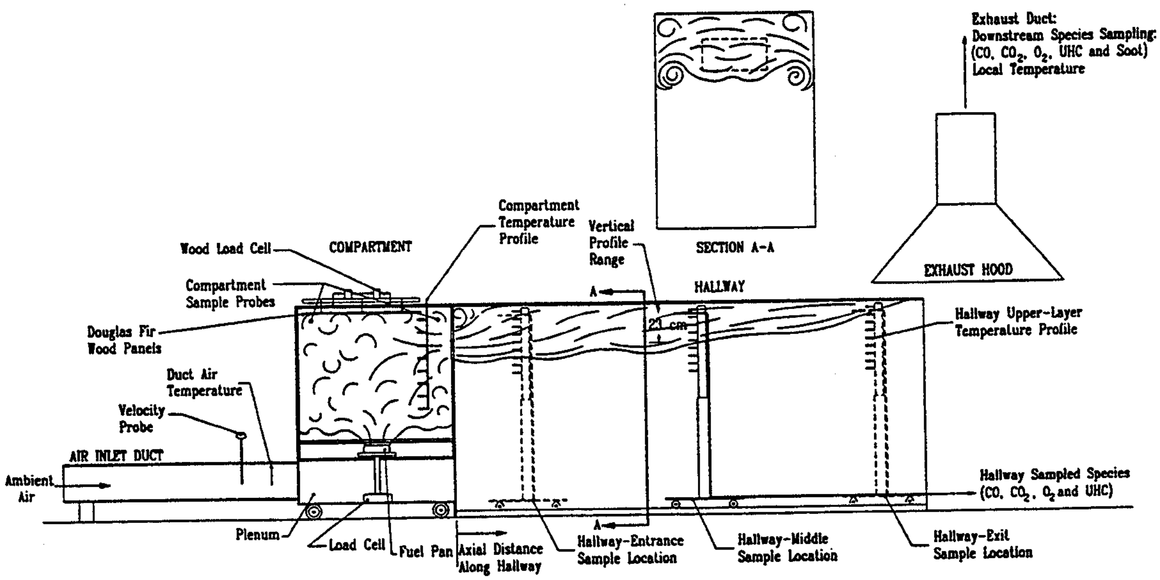

Fig. 1. The experimental facility showing the window-case with the external burning produced from an underventilated fire inside the compartment with a wooden ceiling.

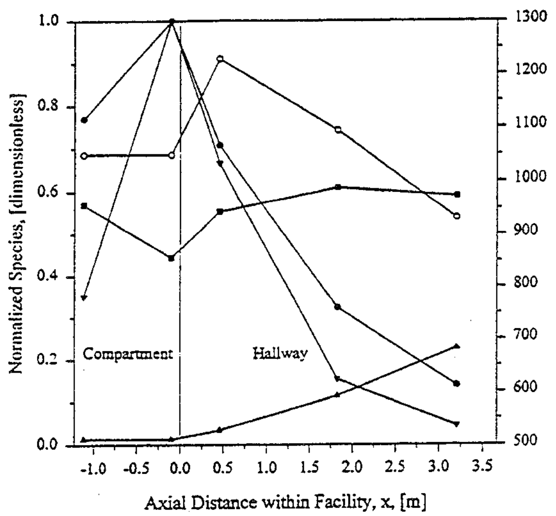

Fig. 2. Window-case with a non-combustible ceiling. Average global equivalence ratio of 2.50; average hexane fire size 535 kW. Normalizing values: ●-CO(4.08%), ▼-UHC(6.35%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

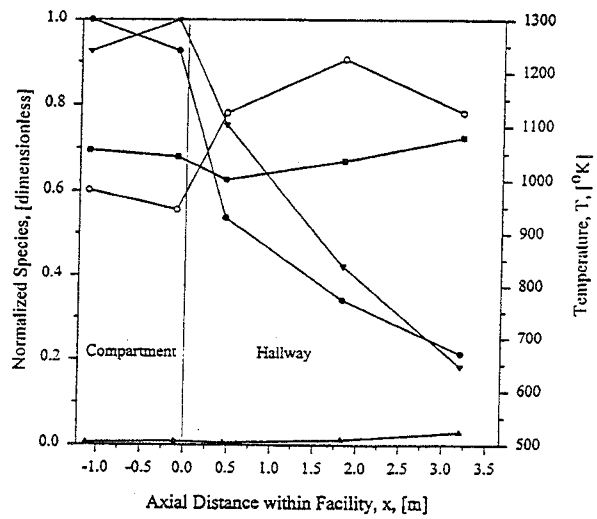

Fig. 3. Window-case with a combustible ceiling. Average global equivalence ratio 4.77; average hexane fire size 446 kW; average wood fire size 685 kW. Normalizing values: ●-CO(13.6%), ▼-UHC(7.88%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

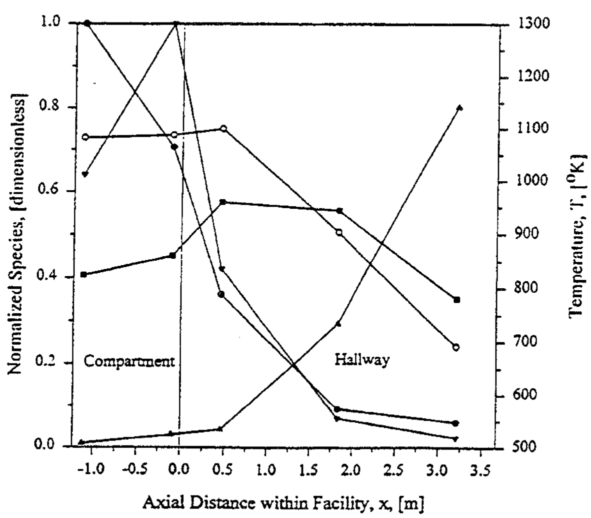

Fig. 4. Door-case with a non-combustible ceiling. Average global equivalence ratio 2.23; average hexane fire size 546 kW. Normalizing values: ●-CO(7.0%), ▼-UHC(5.15%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.

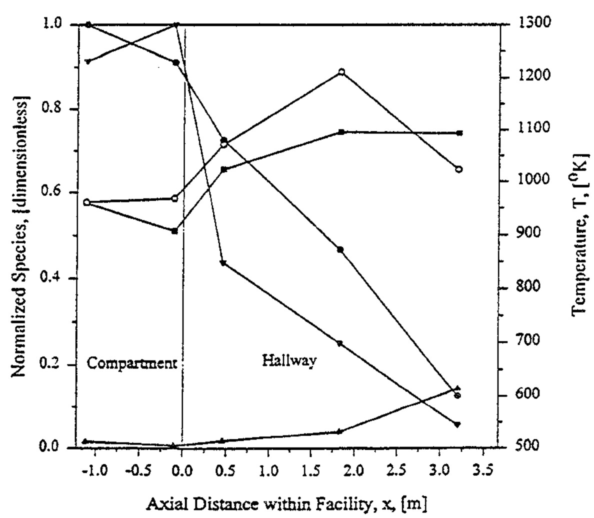

Fig. 5. Door-case with a combustible ceiling. Average global equivalence ratio 4.25; average hexane fire size 495 kW; average wood fire size 902 kW. Normalizing values: ●-CO(10.9%), ▼-UHC(8.27%), ■-CO_2(20%), ▲-O_2(10.5%) and O-Temperature.